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EARLY LIFE HISTORY OF PACIFIC HERRING: RELATIONSHIPS OF LARVAL DISPERSAL AND MORTALITY TO ENVIRONMENTAL CONDITIONS

FINAL REPORT OF PORT MOLLER PLANNING STUDY

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Abstract

A review of the scientific literature on the transport of pelagic fish eggs and larvae by oceanic and estuarine transport systems shows that a strong link is believed to exist between transport and survival of young fish, particularly for Pacific herring, Clupea harengus pallasi, larvae. Until recently, most studies of this subject were semi-quantitative and so could not be used to reject hypotheses that explain apparent coupling between oceanographic phenomena, survival of fish eggs and larvae, and subsequent recruitment in fish populations. However, recent advances in hydrodynamic modelling and in computational hardware have made feasible the direct integration of three dimensional, time-varying hydrodynamic computations over the appropriate time and space scales. It is no longer necessary to resort to semi-quantitative methods.

This report recommends that the Generalized Longitudinal, Lateral and Vertical Hydrodynamic and Transport (GLLVHT) model (Edinger and Buchak 1985) be used for studies on the population dynamics of herring larvae in Port Moller, Alaska. The structure of the model is briefly summarized. A computational grid with 250 to 327 cells and a cell area of 3.06 km^2 is established for the Port Moller area. The oceanographic and meteorological data required to initialize, validate and verify the model is summarized.

A preliminary sampling plan is prepared for Port Moller based on the data requirements of the GLLVHT model. Mobilization must begin by mid-April and the field program should run to the end of July. Oceanographic conditions are expected to be transient during the sampling period, so Port Moller should be instrumented during the study. Water pressure sensors should be placed at the western entrance to Port Moller and near Bear River. A current meter may be required near Frank's Lagoon. Temperature and salinity should be measured along the boundaries of the system as well as at each plankton station. A meteorological station should be established near the entrance to Port Moller, and flow rates of at least two of the major tributaries draining into Port Moller should be measured.

At least 26 plankton stations must be sampled once every 2 to 4 d. Three stations must be established along the boundary of the system, and the remainder should be placed on longitudinal and lateral transects within Moller and Herendeen Bays. Series of horizontal tows at different depths should be taken at some of the deeper stations, whenever it is logistically possible.

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Acknowledgements

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1.0 Introduction

1.1 Objectives of the study

Triton Environmental Consultants Ltd. (formerly Envirocon Pacific Ltd.) was contracted by the Ocean Assessments Division of NOAA in June, 1989, to conduct a reconnaissance and planning survey of Pacific herring, Clupea harengus pallasi, larvae of Port Moller, Alaska. This contract had two phases. The first phase was to measure the densities of larvae. McGurk (1989c) reported that there was a major spawning of herring larvae in Port Moller on May 29, 1989, and recommended proceeding to the second phase.

Phase II consists of a review of the state of the art in computer modelling of the transport and population dynamics of pelagic fish eggs and larvae, recommendations on the most appropriate modelling technique, and a preliminary plan for sampling herring eggs and larvae in Port Moller and for collecting environmental data that would satisfy the data requirements of the models. This document is the final report of the second phase of the Port Moller reconnaissance and planning project. It consists of a report on hydrodynamical modelling that was prepared by J. E. Edinger Associates, Inc. for Triton Environmental Consultants Ltd. (section 2.0), and a preliminary sampling plan for Port Moller based on the recommendations of their report (section 3.0).

1.2 Background

The need for computer modelling of the population dynamics of Pacific herring larvae in Alaska was first identified by McGurk (1989b) in his report on the early life history of herring larvae in Auke Bay, Alaska. This recommendation was based on the finding that the growth and condition of herring larvae in Auke Bay were only weakly limited by food because food density was relatively high throughout the study period. Thus, non-trophic factors such as offshore dispersal and predation may have been as important to the survival of the fish as food densities. This finding was consistent with research that has indicated that the mortality of eggs and larvae of some species of fish is a multifactor process involving dispersal and predation, and that it was not solely determined by the density of food in the first-feeding stage as Hjort (1914) proposed (Stevenson 1962, Frank and Leggett 1982, Moller 1984, Iles and Sinclair 1982, Taggart and Leggett 1987, McGurk 1989a).

Even in species in which food density is a critical factor in the survival of larvae, as it is for northern anchovy, Engraulis mordax, in southern California (Lasker 1975, Peterman and Bradford 1987), the interaction between the fish and patches of their food of the critical density for successful feeding and growth is mediated by oceanographic and meteorological processes, which may best be synthesized and studied using hydrodynamic modelling.

The role of dispersal has particular importance in the study of the population dynamics of Pacific herring larvae because several authors have proposed that it is the critical factor that determines survival of the larvae. Stevenson (1962) proposed that the success of a year class of Pacific herring from Barkley Sound, British Columbia, was determined by how many larvae avoided being swept offshore to unfavorable habitat. Two decades later Iles and Sinclair (1982) proposed a physical mechanism that may underly Stevenson's (1962) "transport" hypothesis. They suggested that Atlantic herring, Clupea harengus pallasi, only spawn in "retention zones", which are defined as relatively shallow regions of coastal water that are well mixed by tide-driven turbulence and which are surrounded by deeper stratified water. It is not clear from their work whether larvae are expected to be actively or passively retained in a zone, but the probability of survival of the larvae is supposed to be directly related to their probability of remaining within the zone.

A second reason for examining the dispersal of Pacific herring larvae is related to the underlying purpose of these researches: to assess the potential impact of oil and gas development on Alaska's continental shelf on herring resources. It is important to know where the herring larvae go once they hatch in order to guage the probable impact of an oil spill in coastal waters. Do larvae stay in coastal embayments throughout the larval and juvenile stages? or is a significant proportion of the population transported offshore or along shore?

A third reason for studying dispersal is that it is necessary in order to obtain accurate estimates of mortality rates of larvae. This topic is examined in detail in section 2.0.

In summary, any study of the early life history of Pacific herring in Alaska should include measurements of their growth, mortality and dispersal, and it should also include measurements of the interactions of the larvae and their biological and physical environments. Hydrodynamic modelling is an essential component of both activities.

Modelling of dispersal of fish eggs and larvae cannot be done without close cooperation between biologists and physical oceanographers. Therefore, Triton Environmental Consultants Ltd. decided to obtain expert advice from J. E. Edinger Associates, Inc. in order to plan a sampling regime for Port Moller herring larvae that would be compatible with hydrodynamic modelling.

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2.0 Numerical hydrodynamics, transport and fate of fish larvae: a review of the subject and a plan for modeling the transport and population dynamics of Pacific herring larvae of Port Moller, Alaska

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2.1 Introduction

Norcross and Shaw (1984) recently reviewed the biological literature on the oceanic and estuarine transport of planktonic fish eggs and larvae and concluded that, in general, the production of fish eggs and larvae appears to be coupled with natural oceanographic transport systems such as gyres, coastal currents and other directional current systems. Under "normal" conditions eggs and larvae that are released into such systems are transported towards sources of food and away from predators, but under unusual conditions eggs and larvae may be transported to areas of low food production or high predator density, or not transported at all, and so the young fish may suffer catastrophic mortality. In this way oceanographic transport is believed to play an important role in determining the success or failure of year classes.

There are exceptions to this generalization, as Marliave (1986) has shown for the larvae of rocky intertidal fish. Dispersal in these species is quite limited and is determined by oceanographic features on the scale of meters rather than kilometers. There are also a variety of specialized hypotheses on the coupling of oceanographic features and egg and larval survival that have been developed from research on unique features of the early life histories of single species of fish. Some of the most well-known of these hypotheses are Stevenson's (1962) "transport" hypothesis for Pacific herring, Clupea harengus pallasi, larvae, Laker's (1975) "stability" hypothesis for northern anchovy, Engraulis mordax, larvae (see also Peterman and Bradford 1987), Iles and Sinclair's (1982) "retention zone" hypothesis for Atlantic herring, Clupea harengus harengus, larvae, and Frank and Leggett's (1982) "safe-site" hypothesis for capelin, Mallotus villosus, larvae.

In most of the studies reviewed by Norcross and Shaw (1984), the coupling of the fate of fish eggs and larvae with their transport by advective and dispersive processes was done in a semi-quantitative manner. Water circulation patterns were identified from limited models or field measurements and egg and larval distributions were measured from plankton tows, and then the two sets of observations were linked by speculative hypotheses. An exception to this generalization is Talbot's (1977) study of the dispersal of plaice, Pleuronectes platessa, eggs and larvae in the Southern Bight of the North Sea.

In the past decade it has become clear that further progress in the field of fisheries oceanography requires, among other things, much more accurate information on the population dynamics of fish eggs and larvae and on the dynamics of their prey and predators than has so far been gathered because without accurate estimates of mortality and dispersal the hypotheses listed above cannot be tested and rejected. The problem is a technical one of reducing the error around the estimates of mortality and dispersal so that temporal and spatial variation in mortality and population density can be compared to temporal and spatial variation in the density of prey and predators. The solution to the problem is to measure all losses of eggs and larvae from the sampling area that are due to advection and dispersion. Natural mortality is the loss rate remaining after these rates have been subtracted from the total loss rate. This kind of analysis is not possible with semi-quantitative methods.

Several recent papers have addressed this problem by developing simple mathematical models of losses due to advection and dispersal. Munk et al. (1986), Heath and MacLachlan (1987) and McGurk (1989b) used models of the dispersion of patches of herring larvae. Although the models were derived from equation (1) below, their use was restricted by several gross assumptions:

(1) only the distribution of larvae was modelled, there was no link between the physical and biological environments;

(2) larvae were assumed to exist as patches residing in an environment with no boundaries;

(3) the shape of the patches of larvae was assumed to be symmetrical, either a perfect circle or an ovoid;

(4) the vertical axis was ignored by depth-averaging the densities of herring larvae;

(5) rates of diffusion and advection along the two horizontal axes were assumed to be constant with time and distance from the origin; and

(6) mortality rates were assumed to be constant with time.

Taggart and Leggett (1987a, 1987b) used time-series models, regression models, and simple simulation models to calculate the movement of capelin larvae.

In this report, we intend to show that recent advances in time-varying hydrodynamic and transport modeling as well as advances in computer hardware have made feasible the direct integration of three dimensional, time-varying hydrodynamic and transport computations without resorting to the use of simpler semi-quantitative descriptions (Edinger and Buchak 1980, 1985). These computations produce input-output mass transport coefficients which can used by biologists to calculate time-varying coefficients of mortality and dispersal of fish larvae at any place or time that the biologists decide is important.

Spawning of Pacific herring takes place along sheltered coasts in semi-enclosed embayments. Numerous field studies reviewed by McGurk (1989a,b) (see also recent papers on Atlantic herring larvae by Townsend et al. 1986, Henderson 1987, Heath et al. 1988, Heath and Rankine 1987, Stephenson and Power 1988, and Chenoweth et al.

Dx, Dy, Dz = dispersion coefficients in each of the coordinate directions; and
Z = mortality rate.

The term on the left-hand side is the local change in storage per unit volume over time. The first three terms on the right-hand size represent the change in advection with currents in each of the coordinate directions. The second three terms represent the change in dispersion with mixing in each of the three coordinate directions. The last term is linear mortality over a time increment or a function of age-class.

Conceptually, the egg and larval transport problem is an initial value problem. Given the initial spatial distribution of the eggs or young larvae,. the spatial distribution over time can be determined by currents, dispersion and mortality, subject to the boundary conditions of no transport through physical or shoreline boundaries and exchange at open boundaries.

Practically, as indicated by McGurk (1989b), the problem is to determine the instantaneous mortality, Z, as a function of age given the spatial distributions of the eggs and larvae at different ages and at different times. In many cases Z has been calculated by assuming that the egg and larval patches are observed over a very large volume with very low densities at their boundaries, e.g. Hewitt et al. (1985). Therefore, the advective and dispersive exchanges at the boundaries can be neglected and mortality can be evaluated by equating change in storage with mortality, i.e $\partial N/\partial t = -ZN$, and fitting some type of relationship to the balance. In other cases where boundaries could not be located because the sampling area was too small to overlap the margins of the patch of larvae, e.g. McGurk (1989b), advection and diffusion were assumed to be constant with space and time and each term in equation (1), including mortality, was evaluated with non-linear regression techniques.

Both the conceptual and practical problems involve knowing the velocity components U, V, W and the dispersion coefficients Dx, Dy, Dz as functions of space and time. These can be determined from the time-varying three dimensional hydrodynamic relationships. In these evaluations, the velocity components are known to the spatial detail of the waterbody computational grid and the temporal detail of the boundary data. Also, the more spatial and temporal detail with which the velocity components are known, the less important become the dispersion processes.

It should also be noted that the mortality function may be more complex than simple linear decay for some fish eggs and larvae. Hewitt et al. (1985) reported that jack mackerel, Trachurus symmetricus, larvae of the California Bight exhibit a mortality rate that declines exponentially with age, i.e $Z = t^{-b}$. This is known as Pareto-type mortality. Other mortality functions are possible. For example, mortality may be related to the carrying capacity of the environment by the Lotka-Volterra predator-prey relationship

1989), show that the spatial scales of herring larval distributions are of the order of'2 to 20 km horizontally and 10 to 60 m vertically with temporal scales of 10 to 40 d. For semi-enclosed waterbodies and coastal waters of this spatial scale, the computational aspects of determining currents and dispersion is essentially a boundary data problem. This means that computations depend on specifying the open boundary water surface elevations due to tides and winds, the open boundary temperature and salinity structure which determines density driven baroclinic circulation, the water surface meteorological conditions for wind shear, windwave radiation stresses and heat exchange, and freshwater inflows along with the waterbody hydrography. The three dimensional hydrodynamic and transport relationships then generate the circulation and transport to the detail with which the boundary data is specified.

Formulating transport as a boundary data problem also has some prognostic features including determining the changes in abundance of larvae with age that might take place due to different wind, tide, density forcing of circulation, and dispersion at waterbody boundaries.

Establishing the hydrodynamics and transport of fish eggs and larvae as a boundary value problem does not require much more hydrographic and meteorological data than has been used in empirical studies of the interaction of larval abundance and hydrodynamics, e.g. Taggart and Leggett (1987a). Also, the amount of computational effort is not much more extensive than the time-series analyses undertaken in the same study.

2.2 Egg and Larval Transport

As indicated by McGurk (1989b) a starting place for formulating the fish egg and larval transport problem is the basic time-varying three dimensional advective-dispersive conservation relationship with mortality. This can be written in three rectangular coordinate spatial dimensions and time as

$$\partial N/\partial t = -\partial UN/\partial x - \partial VN/\partial y - \partial WN/\partial z + \partial(Dx\partial N/\partial x)/\partial x$$
$$+ \partial(Dy\partial N/\partial y)/\partial y + \partial(Dz\partial N/\partial z)/\partial z - ZN \tag{1}$$

where

N = densities;
U = x-direction horizontal velocity component;
V = y-direction horizontal velocity component;
W = z-direction vertical velocity component;

Z = a(N-K)/K, where a is a constant and K is the carrying capacity of the environment. K may be defined by food density, temperature, salinity, and the spatial distribution of tidal and wind energy dissipation throughout the waterbody, which can be evaluated from the results of the hydrodynamic computations (Garrett et. al. 1978).

A real problem in evaluating the mass balance [equation (1)] is that fish larval sampling takes place over relatively large volumes, and is separated by relatively long time intervals compared to the spatial and temporal detail with which the hydrodynamics can be evaluated. Hence the mass transport due to the detailed currents must be integrated over time and space to coincide with the larval sampling. As shown in section 2.4 below, this problem can be solved efficiently by evaluating transfer coefficients for mass between the larger sampling volumes integrated over the sampling intervals (Edinger and Buchak 1988a, 1988b).

2.3 Hydrodynamics and transport

The hydrodynamic and transport relationships in three dimensions and time are well known from basic physical oceanography, e.g. Pond and Pickard (1978). Fairly recent is their formulation to practical numerical computations that can be efficiently applied over the time and space scales of the larval transport problem, e.g. Edinger and Buchak (1980, 1985), Edinger et al. (1989), Buchak and Edinger (1989a). For purposes of discussion and illustration of the processes included in their evaluation, they are examined below in the form in which they are integrated in the semi-implicit (over time) finite difference form of the GLLVHT (Generalized Longitudinal, Lateral and Vertical Hydrodynamic and Transport) model of Edinger and Buchak (1985).

The hydrodynamic and transport relationships used in GLLVHT are: the horizontal momentum balances for the horizontal velocity components, U and V in the x- and y-coordinate horizontal directions, with z taken positive downward

$$\partial U/\partial t = g\partial z'/\partial x - g/\rho \int_{z'}^{z} (\partial \rho/\partial x)\partial z + fV - \partial UU/\partial x - \partial W/a\ y - a\ WU/\partial z$$

$$+ \partial Ax(\partial U/\partial x)/\partial x + \partial Ay(\partial U/\partial y)/\partial u + \partial Az(\partial U/\partial z)/\partial z + SMx \qquad (2)$$

$$\partial V/\partial t = g\partial z'/\partial y - g/\rho \int_{z'}^{z} (\partial \rho/\partial y)\partial z - fU - \partial UV/\partial x - \partial VV/\partial y - \partial WV/\partial z$$

$$+ \partial Ax(\partial V/\partial x)/\partial x + \partial Ay(\partial V/\partial y)/\partial y + \partial Az(\partial W/\partial z)/\partial z + SMy \qquad (3)$$

Local continuity for the vertical velocity component W of

$$\partial W/\partial z = -\partial U/\partial x - \partial V/\partial y \tag{4}$$

Vertically integrated continuity for the surface elevation, z', of

$$\partial z'/\partial t = -\int_z^h \partial U/\partial x - \int_z^h \partial V/\partial y \tag{5}$$

the constituent transport relationships for n number of constituents, e.g. salinity and heat, of

$$\partial Cn/\partial t = -\partial UCn/\partial x - \partial VCn/\partial y - \partial WCn/\partial z + \partial(Dx\partial Cn/\partial x)/\partial x$$

$$+ \partial(Dy\partial Cn/\partial y)/\partial y + \partial(Dz\partial Cn/\partial z)/\partial z + Hn \tag{6}$$

and an equation of state relating density, ρ, to constituents as

$$\rho = g(C1, C2, ..., Cn) \tag{7}$$

These relationships have six unknowns: U, V, W, z', ρ, and Cn, in six equations, assuming that the momentum and constituent dispersion coefficients: Ax, Ay, Az, Dx, Dy, and Dz, can be evaluated from velocities and the density structure.

In the x and y momentum balances, the right-hand terms are successively the baroclinic or water surface slope, the barotropic or density gravity slope, the Coriolis acceleration, the advection of momentum in each of the three coordinate directions, and the dispersion of momentum in each of the coordinate directions. The baroclinic and barotropic slopes are arrived at from the hydrostatic approximation to vertical momentum, and horizontal differentiation of the density-pressure integral by Leibnitz' rule. The baroclinic slope is the vertical integral of the horizontal density gradient and becomes the major driving force for density induced flows that vary with depth. Even a vertically mixed waterbody, as indicated by salinity and temperature, that has horizontal density gradients can have significant density induced flows.

The hydrodynamic relationships are integrated numerically, implicitly forward in time, by evaluating the horizontal momentum balances as:

$$\partial U/\partial t = g\partial z'/\partial x + Fx \qquad (8)$$

$$\partial V/\partial t = g\partial z'/\partial y + Fy \qquad (9)$$

where U, V and z' are taken simultaneously forward in time and all the other terms are incorporated in Fx and Fy are lagged in time. Equations (8) and (9) are substituted either by cross-differentiation or algebraically from the finite difference forms into vertically integrated continuity to give the surface wave equation of:

$$\partial^2 z'/\partial t^2 + g\partial\left(\int_{z'}^{h}((\partial z'/\partial x)\partial z)/\partial x + g\partial\left(\int_{z'}^{h}(\partial z'/\partial y)\partial z\right)/\partial y = \int_{z'}^{h} Fx\partial z + \int_{z'}^{h} Fy\partial z\right. \qquad (10)$$

The computational steps in GLLVHT on each time step of integration are;

(a) to evaluate Fx and Fy from U, V, W, ρ known from the previous time step;

(b) to solve the surface wave equation for new z' for the spatial grid using a modified form of Gaussian elimination by back substitution;

(c) to solve for new U and V using equations (8) and (9);

(d) to solve for W using equation (4);

(e) tore-evaluate z' from equation (5) for precision; and

(f) to solve the constituent relationships, equation (6).

The semi-implicit integration procedure has the advantage that computational stability is not limited by the Courant condition that $\partial x/\partial t, \partial y/\partial t < (ghm)^{1/2}$ where g is the gravitational constant and hm is the maximum water depth that can lead to inefficiently small time steps of integration. Since the solutions are semi-implicit, e.g. explicit in the constituent transport and the time lagged momentum terms, the stability is controlled by the Torrence condition $U\partial t/\partial x, V\partial t/\partial y < 1$. Hence, the integration time step can be chosen to realistically represent the details of the boundary data which is about 15 min for tides and up to 1 h for meteorological data.

There are a number of auxiliary relationships which enter the computations and bring the boundary data to bear on the evaluation. First, the vertical momentum dispersion coefficient and vertical shear is presently evaluated from (but not limited to) a Von Karman relationship modified by the local Richardson number, Ri, as

$$Az=kL^2/2[(\partial U/\partial z)^2+(\partial V/\partial z)^2]^{1/2}F(Ri) \tag{11}$$

where Ri is the ratio of vertical buoyant acceleration to vertical momentum transfer, k is the Von Karman constant, L is a mixing length that can be a function of depth and time, and F(Ri) is the Richardson number function.

Wind surface stress enters the relationships for each of the coordinate directions as

$$Az\partial U/\partial z|_{z'}=W(Wx) \tag{12}$$

and

$$Az\partial V/\partial z|_{z'}=W(Wy) \tag{13}$$

where W(Wx) and W(Wy) are surface shear functions of wind speed.

In addition to surface windshear, there are two further windwave effects that enter the momentum relationships through the specific momentum terms, SMX and SMy, due to the spatial change in windwave height (H) and period (T) as $g\partial(H^2/T)/\partial x$ and $g\partial(H^2/T)/\partial y$. These are the windwave gradients. One is for windwaves that propagate into the waterbody region from offshore and are not found in the z' boundary elevation record, and for which the spatial distribution of H and T can be found from a wave refraction computation for the waterbody region geometry, e.g. Koutitas (1988). The second is due to the change of H and T along the wind fetch and is a function of fetch length and duration of given windspeeds. These are known as Derbyshire-Draper relationships. The windwave gradients also decay with depth from known windwave properties, but fundamentally they augment the longwave barotropic slope by the difference in average wave heights along the coordinate direction and enter directly into the momentum balance.

Bottom friction enters the computations through a Chezy friction relationship as

$$Az\partial U/\partial z|_{h}=(g/Ch^2)U^2 \tag{14}$$

$$Az\partial V/\partial z|_{h}=(g/Ch^2)V^2 \tag{15}$$

where Ch is the local Chezy friction coefficient and h is the bottom elevation at which bottom friction is evaluated.

The horizontal momentum and constituent dispersion coefficients: Ax, Ay, Dx, and Dy, have not been adequately evaluated within three dimensional numerical models but are thought to be primarily a function of the scale of the computational grid. In GLLVHT they are presently evaluated from grid size using an Okubo (1971) length scaling. Experience has shown that the velocity computations, and hence advection and dispersion in the constituent relations, become less sensitive to the horizontal momentum and constituent dispersion coefficients the more detailed the integration time step and spatial detail.

The source and sink terms, Hn, in the constituent balances, equations (6), depend on the constituent being examined. For heat, the source and sink terms are mainly for surface heat exchange, radiation attenuation through the water column and advective sources such as river inflows. Surface heat exchange includes incoming shortwave solar radiation and longwave atmospheric radiation, their reflective loss components, and the water surface temperature dependent processes of back radiation, evaporation and conduction. These terms are evaluated to different degrees of detail ranging from the heuristic equilibrium temperature relationships of Edinger et al. (1974) to the complete term by term heat budget methods of Jirka et al. (1978) in subroutines to the hydrodynamic and transport models depending on the detail with which meteorological data is available.

For egg and larval transport, as expressed in equation (1) which is identical to equations (6), the major source and sink term is egg and larval mortality that can be expressed and evaluated in many different ways. In principle, the egg and larval transport problem could be evaluated directly from equations (6).

2.4 Mass transport relationships

Compared to the temporal and spatial detail with which the numerical hydrodynamics and transport can be resolved, egg and larval sampling takes place over finite volumes at finite times. For example, Fig. 2.1 shows the volumes used by McGurk (1989c) for reconnaissance surveys of Port Moller. Sampling of each of these volumes took at least 2 d because of the distances that the research vessel had to travel. For comparison, Fig. 2.4 shows the 1750 m x 1750 m grid being examined for hydrodynamic and transport computations in three dimensions at about 15 min intervals. This grid will be described in greater detail in section 2.6. It is expected that the egg and larval sampling volumes will be refined with more horizontal and vertical detail in later sampling, but that they will still be of relatively large size compared to the size of the grid shown in Fig. 2.4 due to net tow distances and spatial coverage. It is expected that future egg and larval sampling will be at time intends of days with the added logistical complication that not every sampling volume will be sampled on each day.

The problem is to integrate the hydrodynamic and transport results over time and space from the detailed grid shown in Fig. 2.4 to the regional volumes and sampling intervals of the larval sampling typified by Fig. 2.1. One method described by Lawler et al. (1988) is to compute from the detailed model the horizontal and vertical fluxes over the interfaces of the larger scale regional volumes used for larval transport and then integrate these fluxes through time. This is the same as constructing a circulation box model for the larval regions. This method has the complication that integrating the detailed velocities over space and time introduces additional dispersive and transport terms, as shown by Hamrick (1987). These terms must be accounted for in the larger scale mass transport model. Also, when integrating over many tidal cycles there is the problem of accounting for Stokes transport due to surface layer variations.

A method that overcomes the above difficulties is to use the detailed hydrodynamic and transport model to compute mass transfers between the larger grid regions over the time period of integration in order to obtain time and space averaged mass transport coefficients for independent computations of transport for the larger regions at the larger time steps (Edinger and Buchak 1988a, 1988b). For these computations, the larger regional grid is superimposed on the detailed grid in any desired manner.

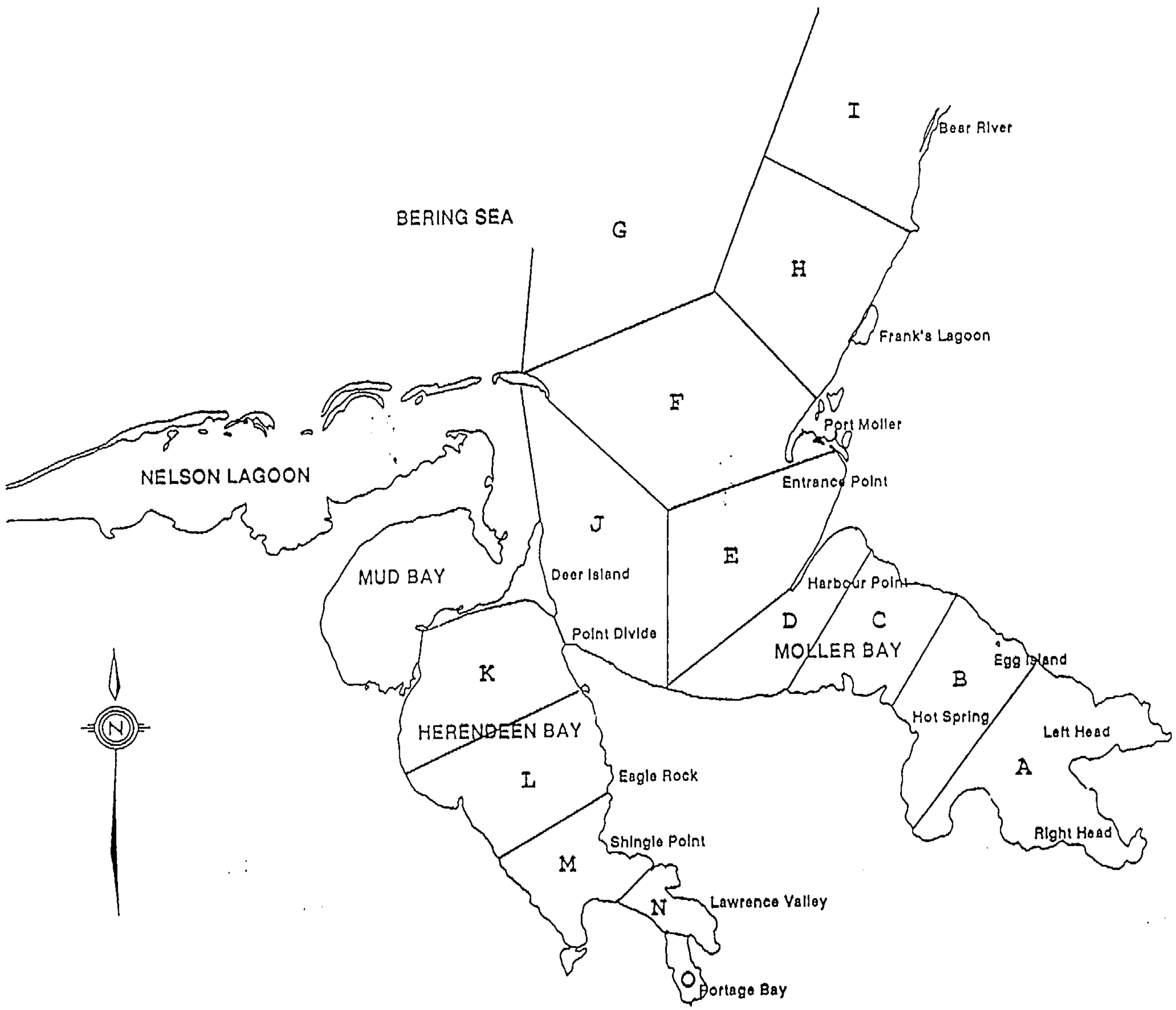


Fig. 2.1. Map of Port Moller.

The transport coefficients between the regional grid volumes, V_k, where k is the index of the regional grid volume, over the period of integration between sampling periods are determined by initializing the detailed grid cells within a region at a constant constituent concentration CI. Each of the coarse regions is initialized with a different numbered constituent that can be transported throughout the detailed grid by equations (6) and located in any other coarser region at the end of the period of integration. The transport coefficient is determined from the initial mass MI_j in region j and the mass at the end of the period of integration $M_{i,j}$ in region i that originated in region j, or

$$A_{i,j}=M_{i,j}/MI_j \tag{16}$$

where $A_{i,j}$ is the mass transport coefficient from region j to region i and is the fraction of mass transported over the period of integration. For the waterbody, there is a matrix of mass transfer coefficients representing the transport between each pair of coarser regions.

Mass must be conserved over the whole waterbody, and this is maintained by balancing the internal mass transfers against exchange at the open boundaries by evaluating the boundary sinks and sources. At the boundary sink, the transfer from region j out at the boundary, $M_{b,j}$, is determined as

$$M_{b,j}= MI_j- \sum_{i=1}^{kt} M_{i,j} \tag{17}$$

where kt is the total number of coarser regions. The total mass lost at the boundary from all regions becomes

$$MB= \sum_{i=1}^{kt} M_{b,j} \tag{18}$$

and the transport coefficients from region j to the boundary sink become

$$A_{b,j}= M_{b,j}/MI_j \tag{19}$$

and the boundary "volume" of exchange becomes MB/CI.

At the boundary, the source mass into each region is

$$M_{i,b} = MI_i - \sum_{i=1}^{kt} M_{i,j} \tag{20}$$

for which the mass at the boundary is also

$$MB = \sum_{i=1}^{kt} M_{i,b} \tag{21}$$

which assures continuity of the system and can be determined as a check on the computations. The transport coefficients from the boundary to region i are thus

$$A_{i,b} = M_{i,b}/MB \tag{22}$$

and the mass transport relationship for the mass MS_k in each coarse region k then becomes

$$\partial MS_k/\partial t = \sum_{j=1}^{kt} A_{k,j}\, MS_j - \sum_{i=1}^{kt} A_{i,k}\, MS_k + BI_k - BO_k + SS_k \tag{23}$$

where the first term on the right hand side is the mass into region k from all other regions. The second term is the mass out of region k to all other regions. $BI_k = A_{k,b}$ VB CB is the mass in from the boundary where CB is the time varying boundary concentration or density, $BO_k = A_{b,k}\, MS_k$ is the mass out of the region to the boundary, and SS_k are the source and sink rate processes in each region for the particular constituent being examined. Essentially, equation (23) is a time and space integrated form of equation (l), where the transport terms have been replaced by transport coefficients.

The time varying egg and larval mortality rates are incorporated in the source and sink or SS_k term. This term can be evaluated over regions and times from the egg and larval data using equation (23) with the added complication that not all regions are sampled at all times. Different inverse and statistical fitting techniques for performing this evaluation are presently being examined.

The procedure is thus to evaluate the $A_{i,j}$ between sampling times from a "long" run of the hydrodynamic and transport equations, and then use these transport coefficients as input to a simpler program or model to evaluate equation (23). Typically, the hydrodynamic and transport run is a matter of hours on a mini-computer or advanced PC and the separate mass transport equation evaluation from the generated transport coefficients is a matter of minutes. Thus, a mortality function such as the Pareto function could be evaluated from the data by using successive simulation techniques. Also, the simpler mass transport program or model is readily transportable to others for further evaluation.

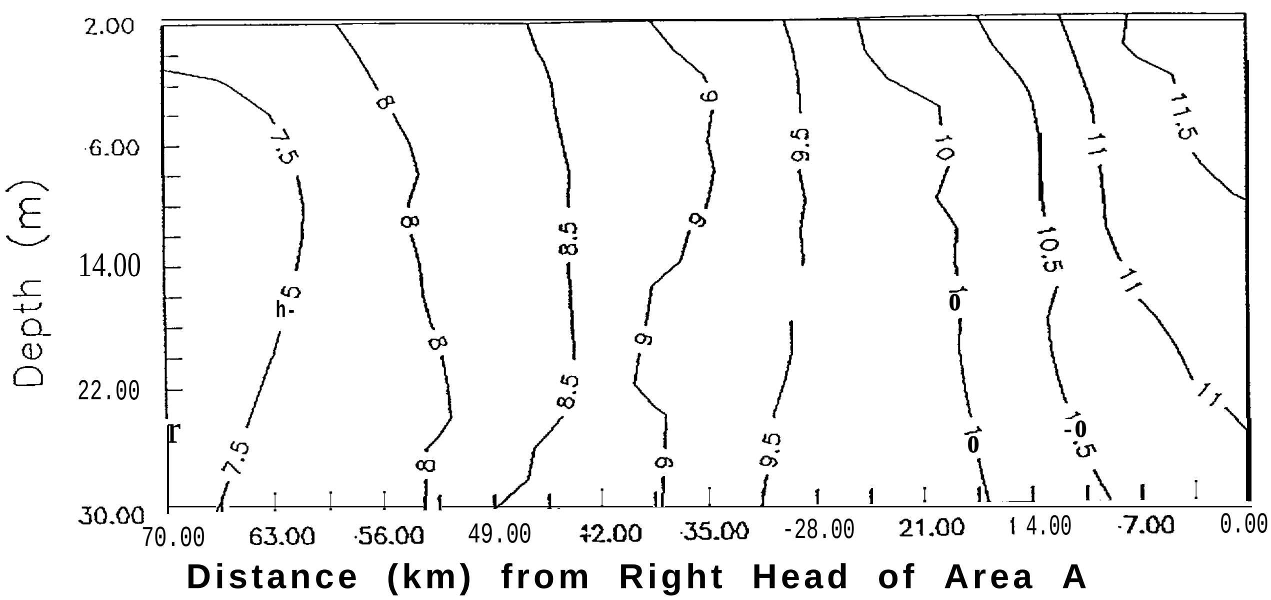
2.5 Port Moller hydrography

This section reviews the existing hydrographic and oceanographic information from McGurk (1989c) and from the "Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska -- Volume II Bering Sea". The information is reviewed to determine the general hydrographic characteristics of Herendeen-Moller Bay from bathymetry and from a limited set of reconnaissance survey temperature and salinity stations, and the general hydrodynamic and meteorological boundary conditions to which these bays are responding. One purpose of this review is to determine the required characteristics of the model configuration.

If Port Moller is defined by a boundary extending across from Point Edward on the west to Entrance Point on the east, then it has a surface area of 5.93 x $10^8 m^2$, a volume of 4.57 x $10^9 m^3$, and a mean depth of 7.7 m (Fig. 2.1). About 27% of the surface area of the bays is intertidal and both Moller and Herendeen Bays are incised by channels of 20 to 30 m deep with depths up to 86 m in Portage Bay of Herendeen Bay. The distance across the boundary between Point Edward and Entrance Point is about 10.1 nm or 18.7 km. Herendeen Bay and Moller Bay are each about 58 km long.

Salinity and temperature profiles are given in McGurk (1989c) for the center of the reconnaissance survey volumes for the period of June 12 to June 14, 1989 (Fig. 2.1). These profiles are shown as composite longitudinal vertical plots through Moller Bay in Fig. 2.2 (transects A-G) and through Herendeen Bay in Fig. 2.3 (transects O-G). It should be noted that the salinity in the head of both bays dropped substantially between June 12 and June 14 due to freshwater inflow.

Temperature (C), Transects A–G (6/12 – 6/14)



Salinity (ppt), Transects A–G (6/ 12 – 6/ 14)

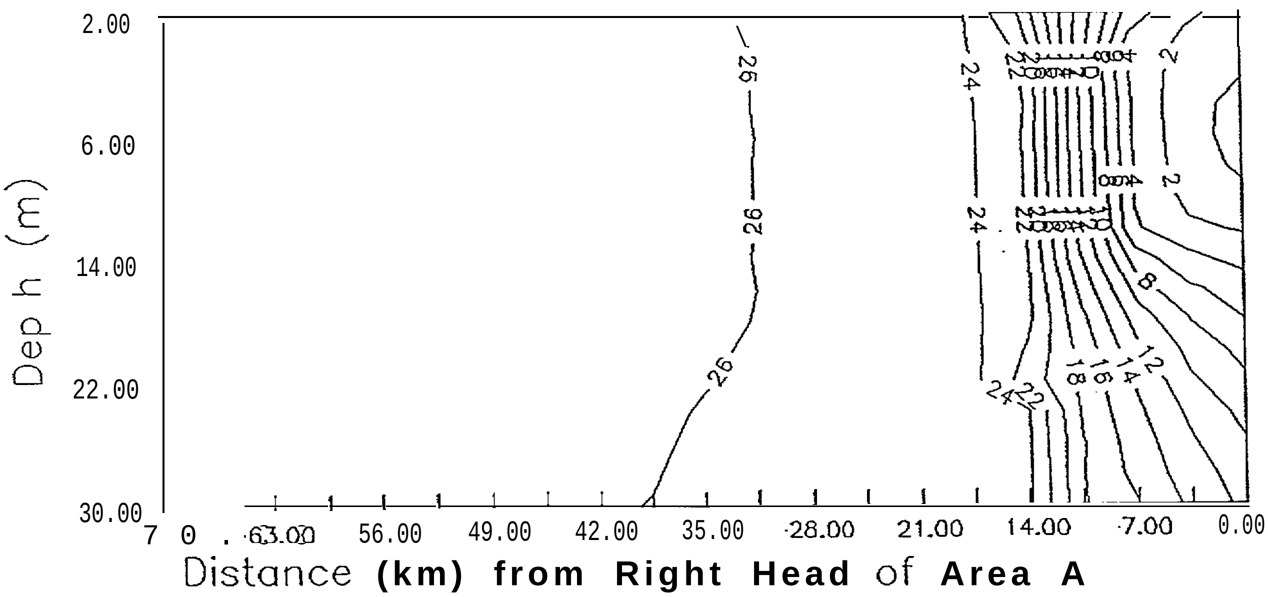
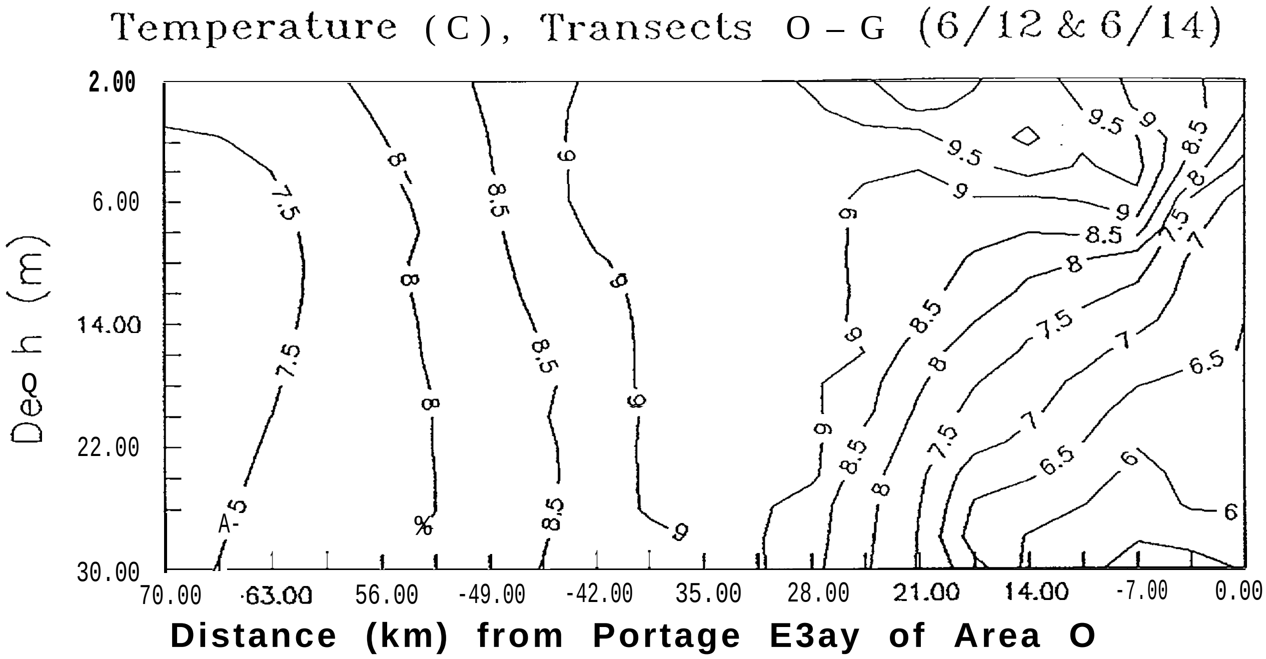


Fig. 2.2. Temperature and salinity isopleths of Moller Bay.



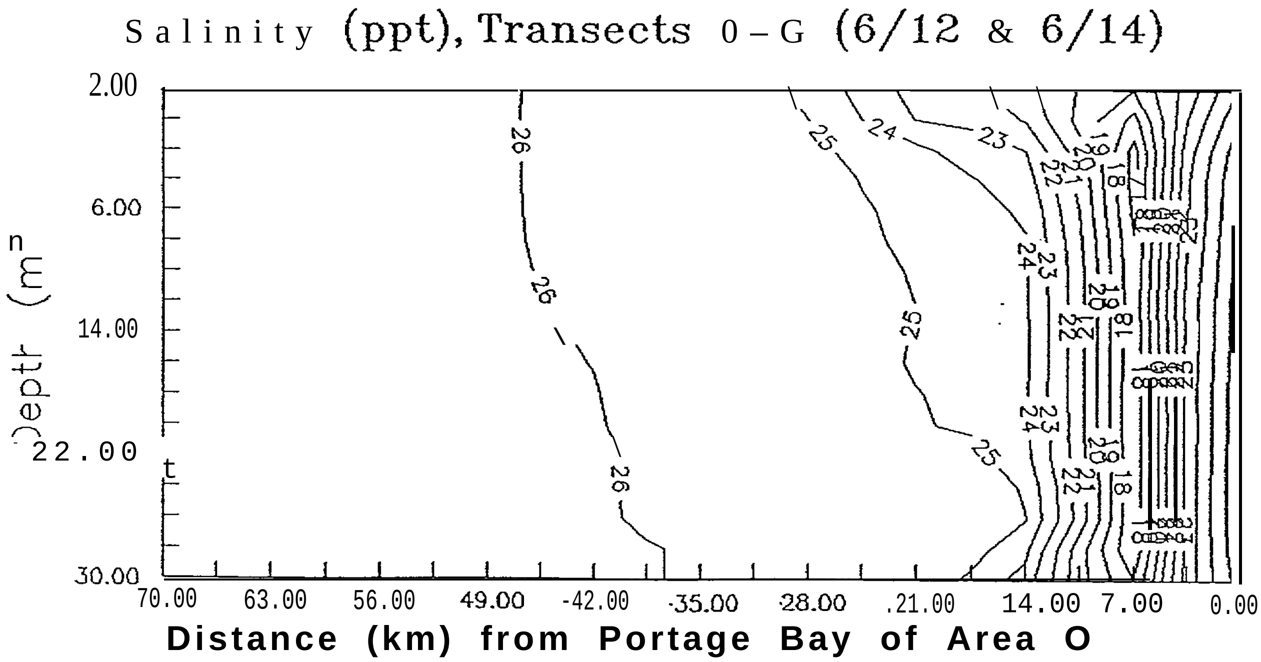


Fig. 2.3. Temperature and salinity isopleths of Herendeen Bay.

Salinities in both bays increase from theheadwaters out to the boundary with a sharp transient longitudinal gradient in the headwaters. The baroclinic gradients are such that this lighter water would rise to the surface layer and spread toward the boundary of the system over the next few weeks. It would create more stratified conditions further down the bays, which would, in turn, create lower layer baroclinic inflows. These inferences on the longitudinal and vertical baroclinic circulation illustrate the short term transient flows and transport that can exist during larval transport periods.

The temperatures in Moller Bay over the reconnaissance surveys decrease longitudinally from about 11.5°C in the headwaters to 7.5°C out near the boundary while the temperatures in Herendeen Bay increase longitudinally from about 7°C in the headwaters to a maximum of 9°C near Mud Bay and then decrease to 7.5°C near the boundary. The lower Herendeen Bay headwater temperatures may be due to a combination of freshwater inflows and the deeper water in Portage Bay. The higher temperatures at the head of Moller Bay and near Mud Bay may be due to circulation and mixing of heat off the surrounding flats.

There is no information on freshwater inflow rates during the reconnaissance surveys. The Atlas indicates a mean annual precipitation for the Port Moller region of 115 cm and, assuming a drainage area of 1 x $10^9 m^2$ and a runoff coefficient of 0.5 to account for evapotranspiration, the mean annual runoff is estimated to be about 18 m^3 S-l. It is expected that most of the runoff occurrs during snowpack melt and would be at a substantially higher rate than the mean rate calculated above.

The Atlas provides some information on tidal and coastal current conditions along the open boundary. It shows tidal ranges increasing northeastward along the coast from 2.4 m near Cold Bay to 4.5 m near Port Heiden. The tides are mixed semi-diurnal and diurnal in period and progressive from west to east. This indicates that there would be a dynamically significant increase in amplitude in tide across the 10.1 nm boundary from Point Edward to Entrance Point. No co-tidal lines are given, but based on the tide being a progressive wave, it is estimated that there is about an 0.8 h phase shift between the two Points.

A mean slope across the boundary could be significant. The Atlas indicates a coastal drift of 1 to 5 cm S-l from west to east parallel to the boundary for which a friction slope could be estimated. The report of Cline et. al (1982) indicates that the coastal drift region extends out from the shoreline to about the 50 m contour. The Atlas indicates that maximum tidal currents along the coast increase from about 30 to 40 cm S-l near Cold Bay and reach a maximum as high as 100 cm S-l near Port Moller.

There is little seasonal salinity and temperature data available off the mouth of Moller Bay. However, Cline et. al (1982) indicates that salinity and temperature are fairly well mixed in the offshore coastal region and influenced by freshwater runoff.

There is sufficient information available above, and from other reports, to construct "typical" tidal, salinity and temperature boundary conditions and to construct mean monthly meteorological conditions to compute "stationary state" circulations within Moller Bay and Herendeen Bay for further description of its circulation. However, as indicated above, conditions during actual sampling periods are likely to be quite transient and should be instrumented for direct measurements during these periods.

2.6 Model configuration

The reconnaissance sampling regions examined by McGurk (1989c) and shown in Fig. 2.1 are essentially laterally averaged segments. Thus, if this were the scale to be examined, then modelling could be performed using the laterally averaged, longitudinal and vertical model presented in Buchak and Edinger (1984). However, it is expected that the egg and larval sampling regions will be refined to incorporate lateral as well as vertical and longitudinal detail, particularly to include the shoreline spawning regions shown in McGurk (1989c). Also, the scales of the initial spawning patches are such that lateral as well as longitudinal and vertical transport are important in describing them.

As indicated previously in section 2.1, the time and space scales of the herring egg and larval distributions are such that the time varying three dimensional GLLVHT hydrodynamic and transport model can be efficiently utilized.

The first step in its setup is to determine an appropriate size of the computational grid. The grid should be sufficiently detailed to incorporate the major features of the shoreline configuration and the bathymetry. It should also allow for computational efficiency, here determined for use on a mini-computer or advanced PC. However, larger computers could be utilized.

Efficient computations can be achieved for configurations with 200 to 300 cells. For a surface area of $5.93 \times 10^8 m^2$, this gives a surface area per cell of $2.9 \times 10^6 m^2$. From the map there appears to be no gain in taking advantage of the model capability to have different ∂x and ∂y. Thus, a square cell configuration of 1750 m appears reasonable for computational efficiency.

Fig. 2.4 shows the Moller Bay-Herendeen Bay map scaled to a 1750 m grid. It shows that the major shoreline configuration is preserved and that the major bathymetric features can be accommodated. For vertical resolution, the GLLVHT model has the capability of layer thicknesses varying with depth so that thinner layers can be used between below the surface and the shallower topography and thicker layers used for the deeper channel regions. This grid can be modified as more information becomes available.

2.7 Boundary data requirements

The boundary condition data required by the GLLVHT model are:

(1) water surface elevations at the open boundary

(2) salinity and temperature profiles at the open boundary;

(3) windspeed and direction for wind surface shear and windwave setup;

(4) for surface heat exchange, shortwave solar radiation or an appropriate surrogate such as cloud cover or percent clear sky, air temperature, dewpoint temperature or relative humidity, and windspeed, and

(5) freshwater inflow rates and temperatures.

Practically, these data are available at different levels of sophistication ranging from:

(1) direct observations of all of the input variables preceding and during the study period of interest; to

(2) reconstructing some of the variables missing from a complete set by various techniques; to

(3) using general information available from the Atlas to construct analytic boundary conditions.

The level of boundary data available in turn dictates the kinds of simulations that can be made ranging from "realtime" data based simulations with a complete set of observed data to "stationary-state" types of solutions for constructed analytic boundary conditions.

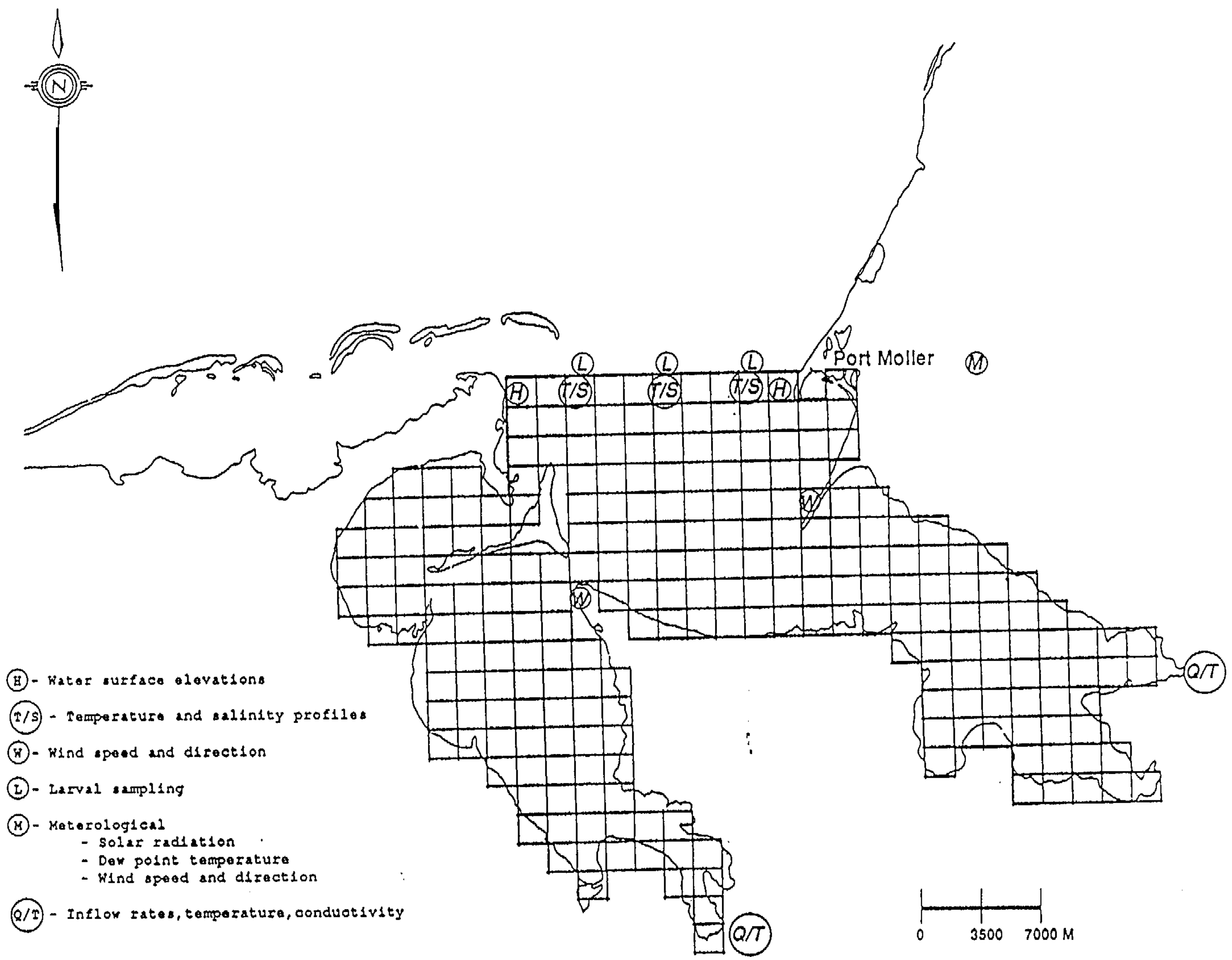


Fig. 2.4. Grid for hydrodynamic model of Port Moller.

Except for a period from May to September 1989, spanning the McGurk (1989c) larval reconnaissance surveys, during which wind speed and direction, and air temperature stations were established at Point Divide and Harbor Point, there does not appear to be extensive realtime data available (Jarvela 1989). Apparently there was no water surface elevation or pressure measurements taken during this period, particularly near the Point Edward to Point Entrance boundary. During this period, extensive current meter data were collected that would serve the purposes of model verification to be discussed later.

The choice of the level of time series boundary data is partially dependent on its availability. Hence, the levels desired are outlined here for each category of data from the most desirable (level 1) to the least available from the literature (the lowest level in each category). They are as follows:

2.7.1 Water surface elevations

Water surface elevations are required at the open boundary to the model, which for this discussion only is assumed to extend from Entrance Point to Point Edward. The following are the choices for water surface elevation data

(1) either water surface elevation or pressure recorders. One near each point. Hourly data acceptable, as is 15 min data, if available; or

(2) one surface elevation or pressure recorder only at Entrance Point. Hourly or more frequent record; or

(3) water surface elevation record from somewhere along the coast within 10 to 20 mi that may already be available; or

(4) calculated amplitudes and phases of tidal constituents: Kl, 01, S1, etc. available for this region from analytic description of tides. The ones given in the NOAA atlas for Bristol Bay are a little too gross, but usable.

2.7.2 Temperature and salinity

The instruments must be placed across the boundary (Entrance Point to Point Edward). The heirarchy of preference is:

(1) three moored T/S chains reading out hourly at 2 to 5 m depth intervals; or

(2) three T/S stations occupied daily from synoptic boat surveys; or

(3) reconstructed boundary T/S for period of interest from historical Bristol Bay data.

2.7.3 Meteorological data

Meteorological data are required for calculations of windshear, windwave radiation stress, and surface heat exchange. There are two meteorological stations: one at Point Divide and the other at Harbour Point. For windshear and windwave calculations only windspeed and directions are required hourly, but for surface heat exchange the required variables are:

(1) short wave solar radiation. Direct measurements or either cloud cover or percent possible sunshine;

(2) air temperature;

(3) dew point or relative humidity; and

(4) windspeed.

The hierarchy is:

(1) direct measurements at the two meteorological stations already in place;

(2) measurements at a nearby weather station or airport within 20 to 30 rni; or

(3) smoothed heating and cooling curves from geographical data. For example, extrapolate compiled coefficients of surface heat exchange and equilibrium temperature curves to the region using historical climatic data for Bristol Bay.

2.7.4 Freshwater inflows and temperatures

The hierarchy of preference is:

(1) direct daily measurements for one or two of the major tributary drainage areas into Moller Bay and Herendeen Bay; or

(2) daily measurements at a coastal river somewhere along the coast that can be extrapolated to the tributaries of either Bay on the basis of drainage areas; or

(3) calculations on a weekly scale from precipitation and snow pack computations. In this case, precipitation data and air temperature data are also required; or

(4) estimates based on mean runoff for the region from geographical data.

2.8 Initialization data

The model needs to initialized to temperature and salinity distributions throughout the Bays about a week before the egg and larval studies begin. Thus, the collection of the boundary data must begin at least one week before egg and larval sampling begins.

The model is initialized and started from rest. The semi-implicit solution of the hydrodynamics and transport is such that the tidal velocities develop within a few tidal cycles, the wind responses develop over the next few days and the slower baroclinic circulation develops over about 1 wk.

The temperature and salinity data for the starting period should be collected to as much horizontal and vertical spatial detail as possible, and in as short a time as possible, within the logistical limits of synoptic surveys. The vertical measurements can usually be collected to the detail of the vertical resolution of the model. Logistically, it may be possible only to occupy centerline temperature and salinity stations to about the detail given in Figs. 2.3 and 2.4, then interpolate to the rest of grid. In that case, it will take the model the equivalent of 1 wk or more to develop the shoreline and shallow area salinity and temperature details in response to freshwater runoff and surface heat exchange.

2.9 Verification data

Validation and verification are two distinct processes in modeling. Validation includes all of the procedures for checking the arithmetic logic of the computations, including the steps leading from the differential forms of the model given in equations (2) through (7), the setups and conversions necessary for entering the time varying boundary data as performed in the TVDS (time varying data selector) routine, and the mass balance inventories required for equations (16) through (23). The GLLVHT model has been validated on numerous occasions and validation is an ongoing process from case study to case study. This process is often called re-validation.

Verification is the step of comparing the model results to some kind of standard. There are different types of verification procedures, but the one of interest for Port Moller is a comparison to observed field data. The degree of verification that can be achieved depends on the amount and kind of field data that can be made available during the period of analysis. However, verification is limited by the level of boundary data available as outlined above and it would not be expected that a model run for constructed "stationary-state" boundary conditions would verify well against data collected for a specific short term study period although the main features might be reproduced.

For salinity and temperature verification, it is expected that T/S profiles will be taken with each egg and larval tow and these are usually adequate data for verification purposes particularly if there are large salinity and temperature gradients and changes over time between egg and larval sampling. Also, time series records of temperature and salinity at specific points provide additional and detailed verification. Temperature and salinity (conductivity) sensors are often attached to current meters as discussed below. The degree of verification that can be expected with the above types of T/S data has been summarized by Edinger and Buchak (1987).

For the purpose of verification, it would be useful to have water surface elevation recorders in the bays independent of the boundary data elevation recorders. These should be deployed as far from the boundary as possible, preferably one in Portage Bay of Herendeen Bay and another in the Right Head of Moller Bay.

Another level of verification uses continuously recording current meters, as shown for a number of cases in Buchak and Edinger (1989b). As discussed above, the use of this level of verification depends on logistics and economics to determine the number of current meters to deploy. However, the deployments given in the attachments to Jarvela (1989) used in the May to September 1989 studies appear to be adequate.

The ultimate verification of the model would be against observed larval distributions initialized from spawning distributions and fecundity. However, since a major purpose of the study is to evaluate mortality rates from the mass balance relationships given in equation (23), the egg and larval distributions will not provide independent data for verification.

2.10 Open coastal boundaries

In this report we have examined the feasibility of combined hydrodynamic, transport and fate modeling for Moller and Herendeen Bays using the well-defined open boundary extending from Point Edward to Entrance Point. However, McGurk (1989c) reports that herring spawning may extend along the coast from Port Moller to Bear River. Also, one of the primary objectives of this research is to assess the direction and magnitude of offshore transport of herring larvae (section 1.0). Neither of these objectives is well served by a model that stops at the entrance to Port Moller. However, to model the open coastal region northeast of the entrance requires a separate analysis.

Fig. 2.5 shows the hydrodynamic and transport modeling with an open coastal boundary and boundary data requirements. The southwest terminus of the boundary is presently established at Point Edward but can be extended to include Nelson Lagoon.

In order to extend to an open boundary, additional time series boundary data is required. This includes water surface elevation or pressure recorders near Bear River and a current meter recorder near Frank's Lagoon.

A current meter record for the open coastal boundary is crucial for model calibration because it is used to determine mean slopes and open boundary tidal conditions near the southwest edge of the grid. This is necessary to allow for the passage of the net northerly drift current that was identified in the hydrography section, and to determine the proper intertidal transport. Calibration of the open boundary tidal conditions from the current meter record will need to be performed by successive simulations.

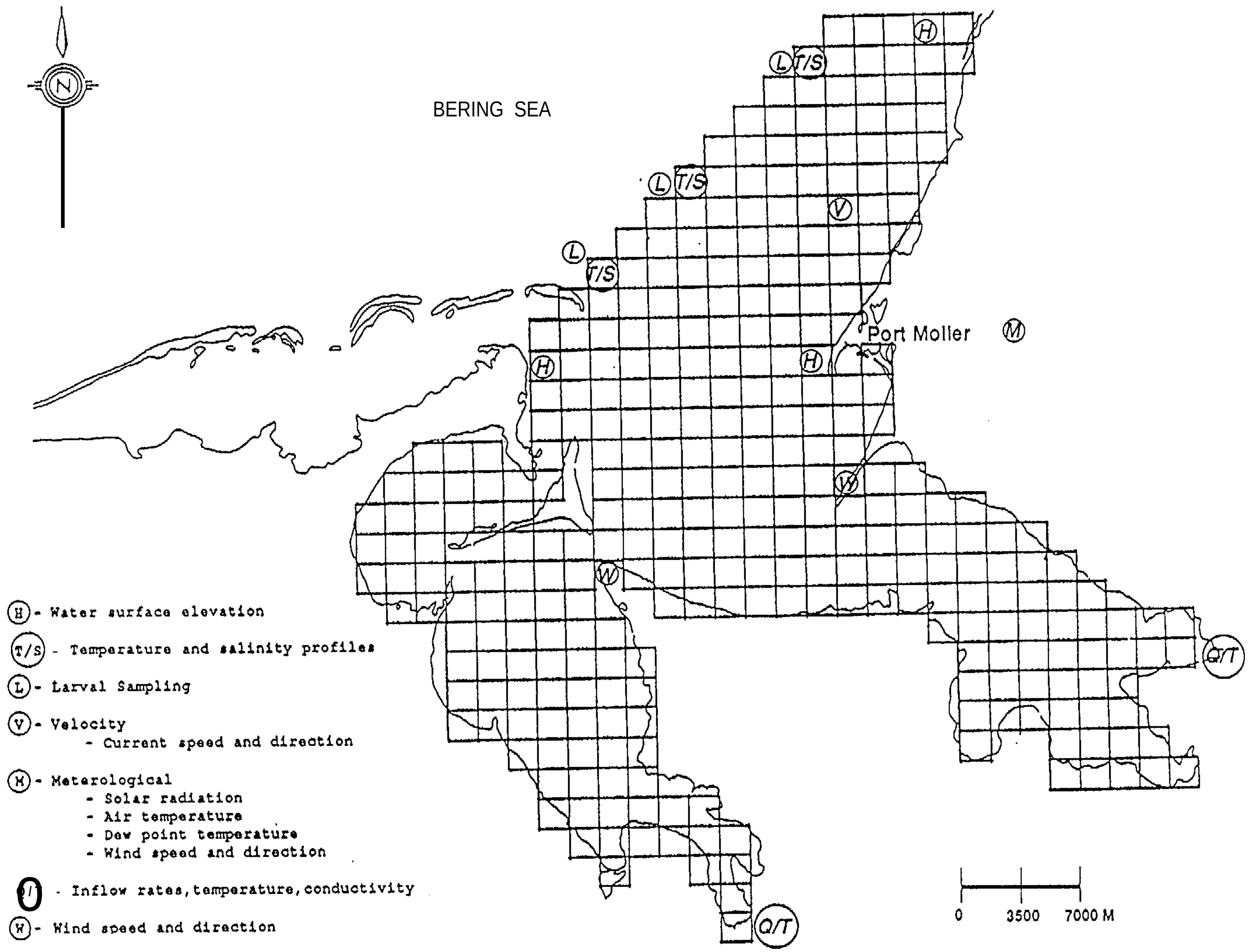


Fig. **2.5.** Grid for hydrodynamic model with an open coastal boundary.

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3.0 Preliminary sampling plan

3.1 Schedule

The field program is expected to last at least 3.5 mo based on an expected mobilization date of April 15 to 17 and an expected end date of July 31.

The earliest date of field activities is determined by the requirements of the hydrodynamic model. As discussed in section 2.8 of this report, the collection of all oceanographic and meteorological data must begin at least 1 wk before the earliest date of sampling of herring eggs and larvae. This is necessary because starting at rest the hydrodynamic model requires a week's worth of data to simulate the complete baroclinic circulation of Port Moller. Thus, in order to have a functioning hydrodynamic model for the earliest dates of egg and larval sampling requires at least 1 wk of previous data collection.

The survey of herring larvae in Port Moller in June 1989 showed that the earliest herring spawning in the Moller Bay had occurred on or about May 15, 1989 (McGurk 1989b). The date of earliest spawn is expected to vary between years, so a conservative estimate of the date on which the search for herring eggs and larvae should begin is May 1. Therefore, oceanographic and meteorological data collection should begin on April 21. This means that the field party should plan to arrive in Port Moller on at least April 17 in order to put the boat into the water, fix any mechanical problems with the engines or the scientific equipment, and position the recording instruments in Port Moller. Problems with malfunctioning equipment are guaranteed to happen, as the 1989 reconnaissance survey showed, and the field schedule should be extended backwards in time in order to account for these difficulties.

The field program should continue until the larvae of the last cohort to hatch into Port Moller has reached an age at which they can no longer be captured with plankton nets. A third cohort probably spawned in Port Moller *in* mid-June of 1989 (McGurk 1989b), which means that larvae entered the water column by June 30. If larvae can be tracked for 30 d after hatch, as were the larvae of Auke Bay, Alaska (McGurk 1989a), then field activities should continue to at least the end of July. Demobilization is not expected to take more than several days.

3.2 Tasks

3.2.1 Mobilization and instrumentation

The first task after arriving in Port Moller is to launch the research vessel and test its engines. Once the boat is functioning properly, the next task is to instrument Port

Moller. As stated in section 2.5 of this report, the oceanographic conditions during the actual sampling period are expected to be quite transient, so data on temperature, salinity, water elevations, freshwater flow rates, and meteorological events must be collected by instruments operating before and during the sampling period.

The number of instruments to be placed in and near Port Moller, and their locations, depends on the objectives of the study and on the resources available to NOAA. One of the objectives of the study is to determine what proportion of the larvae are transported out of or into the Port Moller estuarine complex and what proportion is retained in the complex. This requires using an open coastal boundary (Fig. 2.5) rather than establishing a boundary at the entrance to Port Moller (Fig. 2.4). This is particularly important if spawning happens to occur along the coast between Entrance Point and Bear River as has happened in previous years (McGurk 1989b). However, such a decision would also require placing a current meter near Frank's Lagoon in order to establish tidal conditions at the open boundary. The experience of the 1989 field season in Port Moller suggests that this may be an expensive and time-consuming operation (personal communication, L. Jarvela, NOAA, Ocean Assessments Division, Anchorage, Alaska). In the following discussion I assume that the open coastal boundary will be monitored.

At least one and preferably two water surface elevation or water pressure recorders must be placed at the ends of the boundary stretching from Point Edward to Bear River. A current meter must be placed near Frank's Lagoon. Three temperature/salinity chains must be moored on the open coastal boundary between Point Edward and Bear River. In the absence of T/S chains, the field crew must begin a program of taking T/S profiles at three stations on the boundary at least once a day for the remainder of the field season. At least one meteorological station must be placed near the Port Moller boundary. Finally, a program of monitoring the flow rates of at least two major tributaries that drain into Port Moller, one in Moller Bay and one in Herendeen Bay, must be started and maintained for the remainder of the field season.

3.2.2 Egg stage

The only interaction between research on the egg stage and hydrodynamic modeling concerns the need to obtain daily temperatures and salinities on the spawning beds in order to calculate hatching dates.

3.2.3 Larval sampling

Locations

As discussed in section 2.0, hydrodynamic modelling imposes two limitations on the locations of plankton sampling stations: at least three stations must be placed on the boundary to the system, and samples must be taken along lateral transects as well as longitudinal transects within Moller and Herendeen Bays. Apart from these requirements, the location of other stations should be based on biological and/or logistical criteria.

Fig. 3.1 shows the proposed locations of the plankton stations. Three stations are placed along the open coastal boundary and 3 stations are placed along a transect running between Entrance Point and Point Edward. Inside these two transects is one station at Bear River and a second just off Frank's Lagoon. Inside the Port Moller complex are: four stations along a transect running from Entrance Point to the northwestern end of Herendeen Bay; seven other stations in southern Herendeen Bay; and seven other stations in Moller Bay, for a total of 26 stations. This is not a large number; 15 stations were occupied during the 1989 reconnaissance survey (McGurk 1989b).

Wherever possible stations within Moller or Herendeen Bays have been placed on lateral as well as longitudinal transects. However, this means that some of the stations close to the shores will only be accessible during high tides and great care will have to be taken to avoid snagging the gear on the bottom.

Schedule

The hydrodynamic model does not place any restrictions on the intervals of time between visits to each sampling station. Instead, this will depend on such factors as the state of the weather, the number of available personnel, the schedule of visits to the T/S stations and the flow monitoring stations at the head of Port Moller, and other tasks, e.g. surveys of spawn location and intensity, as well as the requirement to obtain samples of larvae at different ages and stages of development for each cohort.

The Port Moller complex is too large to sample each station every day, but the entire set of stations should be visited at least once every 7 d. Therefore, the expected time interval between samples at each station is about 2 to 4 d.

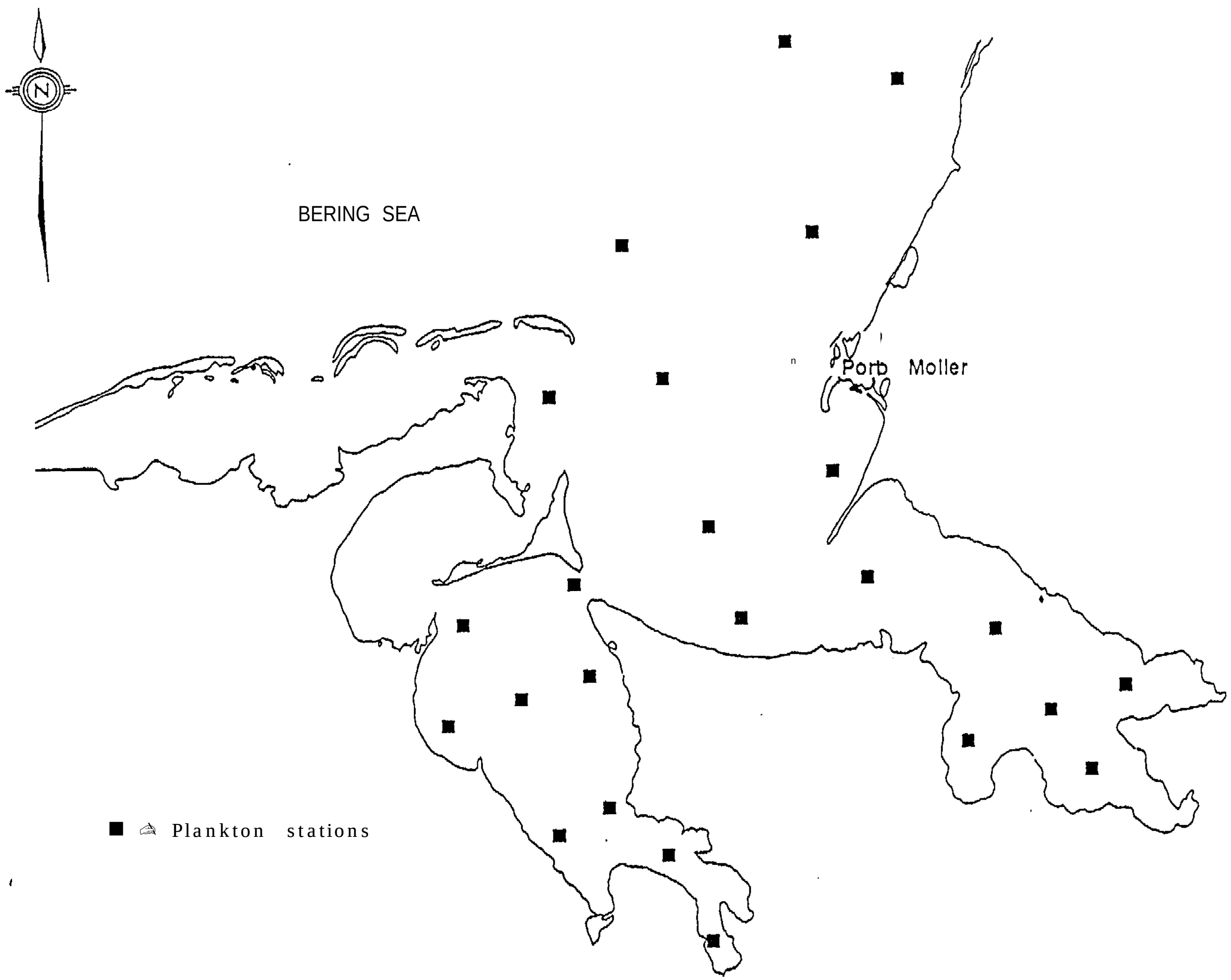

Fig. 3.1. Map of proposed plankton stations.

Depth

Most plankton stations in Moller Bay are too shallow for anything other than oblique tows through the entire water column, but stacks of horizontal plankton tows at two or three different depths may be possible at deeper stations in the Bering Sea and in southern Herendeen Bay. It would be preferable to conduct some series of stacked tows in order to take advantage of the hydrodynamic model's ability to predict transport at depth, and also to investigate the possibility that herring larvae may use vertical movements between counter-flowing currents to retain themselves in coastal embayments (Stephenson and Power 1988). Stacked tows cannot be performed at every station that is sufficiently deep because they are time-consuming.

3.3 References

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